

A Stage-IV CMB experiment, CMB-S4

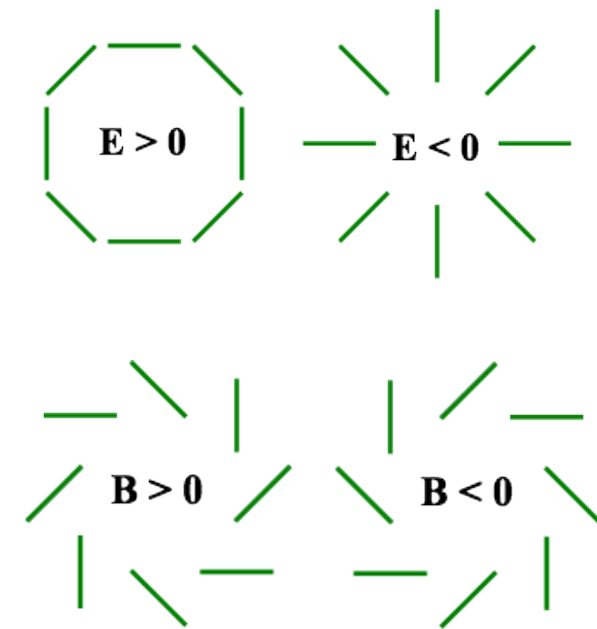
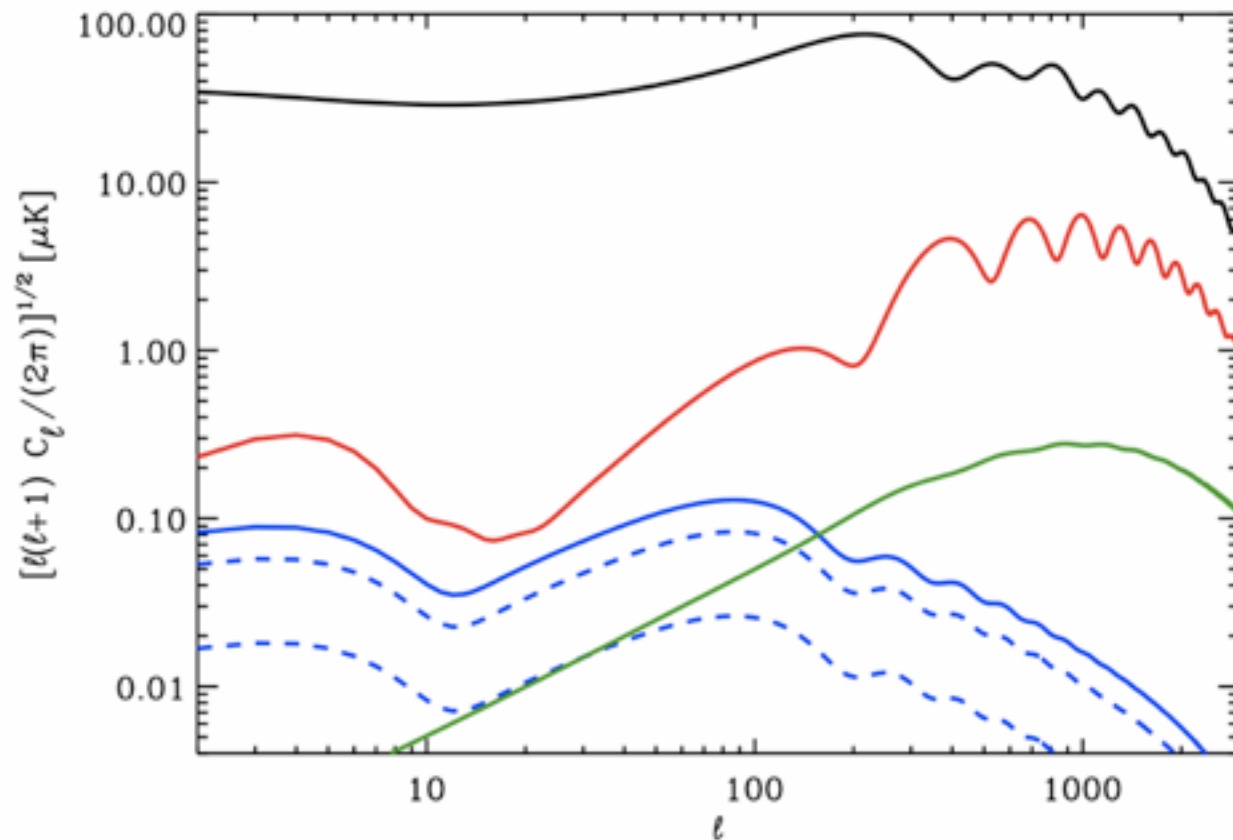
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Assistant Professor

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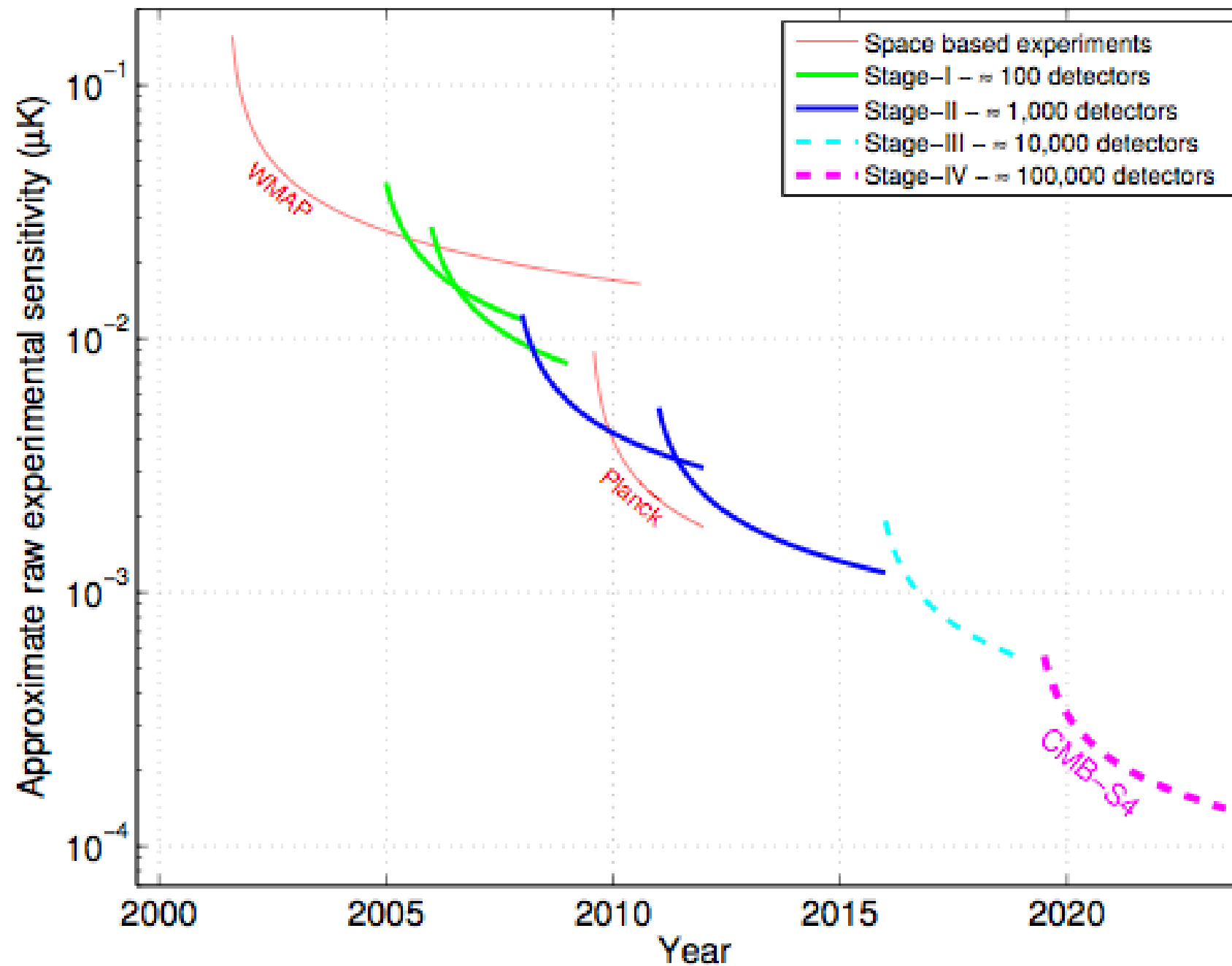
TAUP, Sept. 2013

Goal: fully exploit CMB B -mode physics



- Explore the physics of inflation. r = gravitational wave/density wave
- Measure the Cosmic Neutrino Background. N_{eff} and Σm_ν

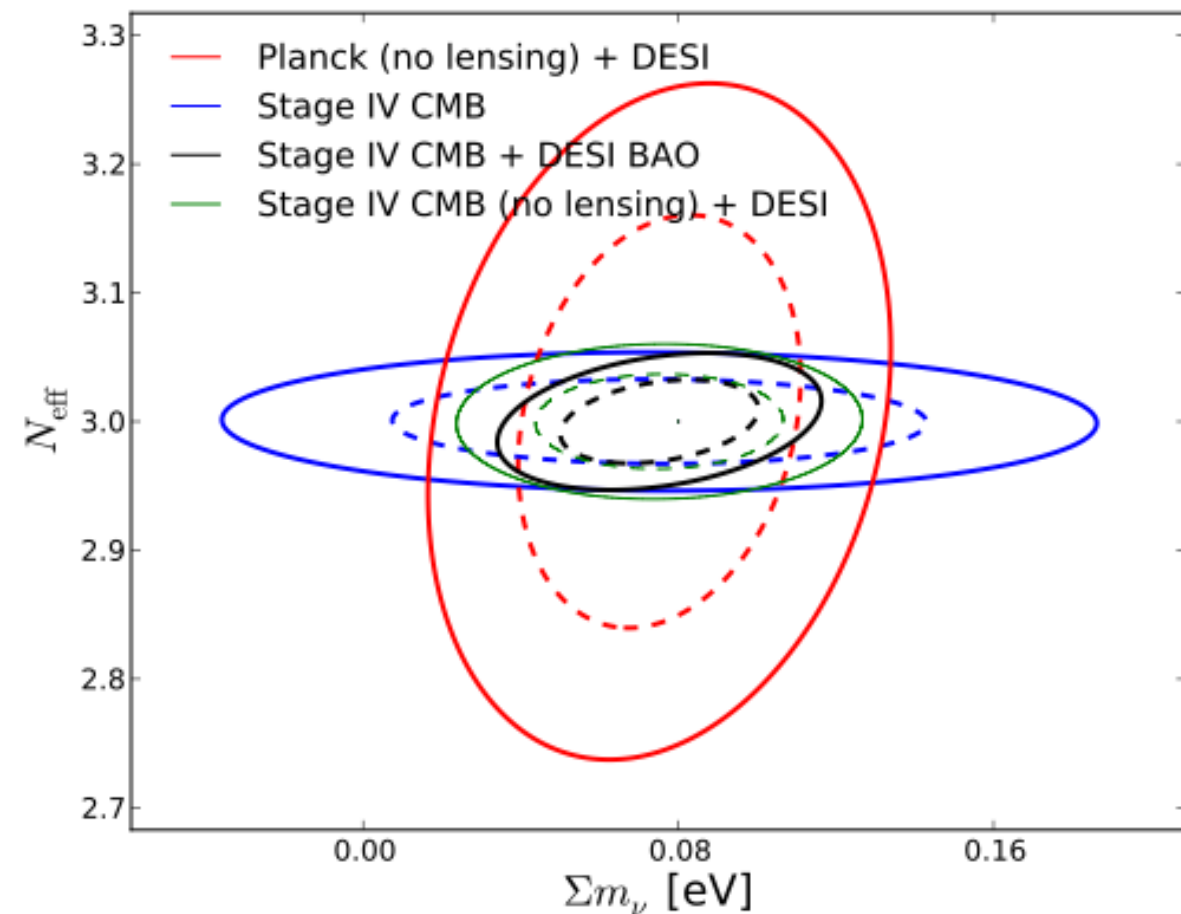
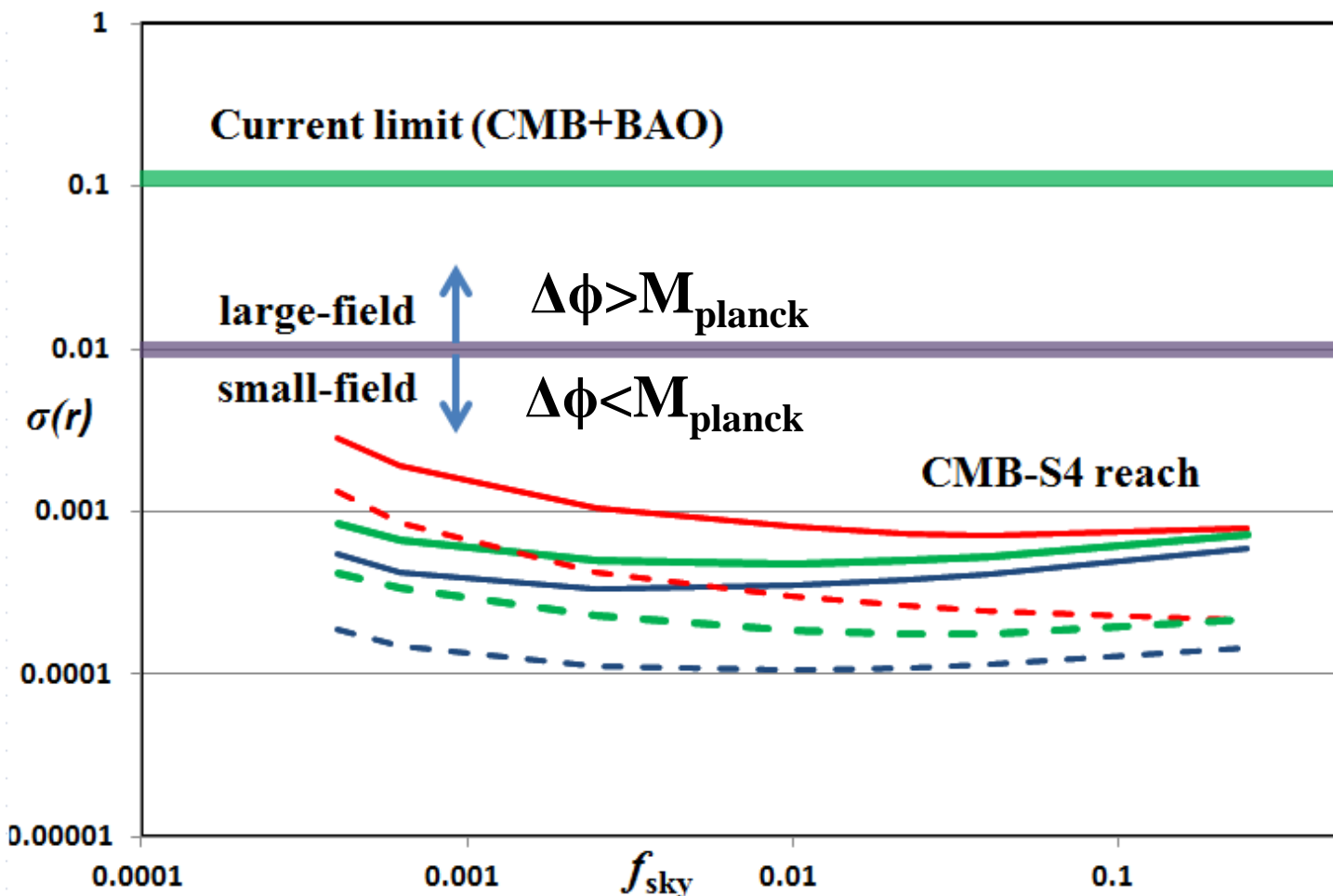
Stages of CMB experiment



Science Reach of CMB-S4

Now: $r < 0.73/0.12$ (from B -modes/temperature); $N_{\text{eff}} = 3.3 \pm 0.27$, $\sum m_\nu < 0.23$ eV

Goal (2020+): $\sigma(r) = 0.001$; $\sigma(N_{\text{eff}}) = 0.02$, $\sigma(\sum m_\nu) = 0.016$ eV



Specs

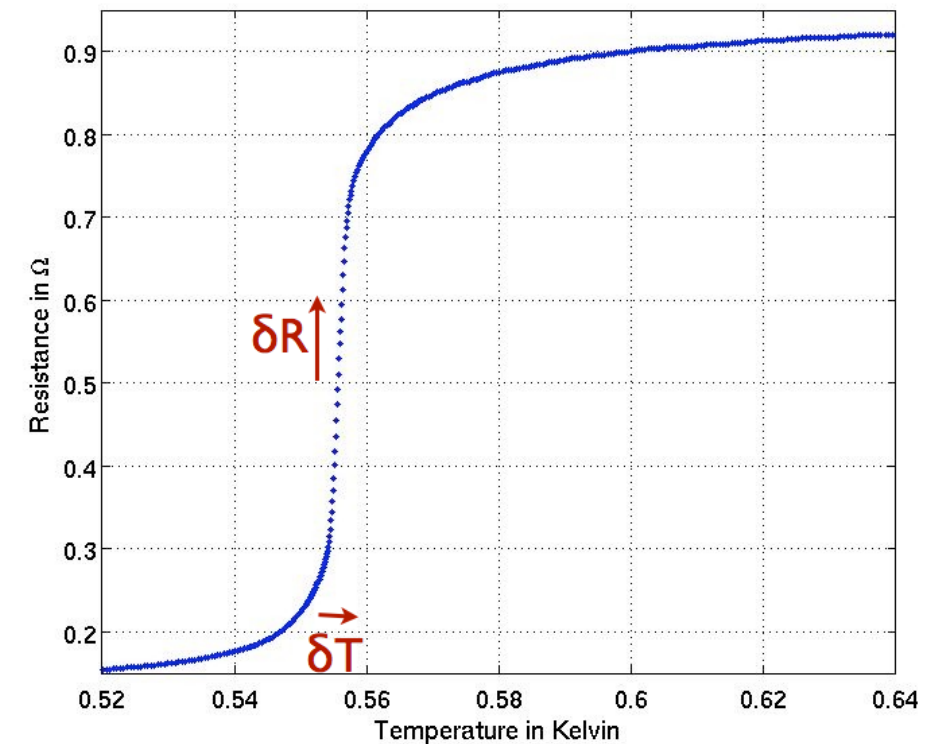
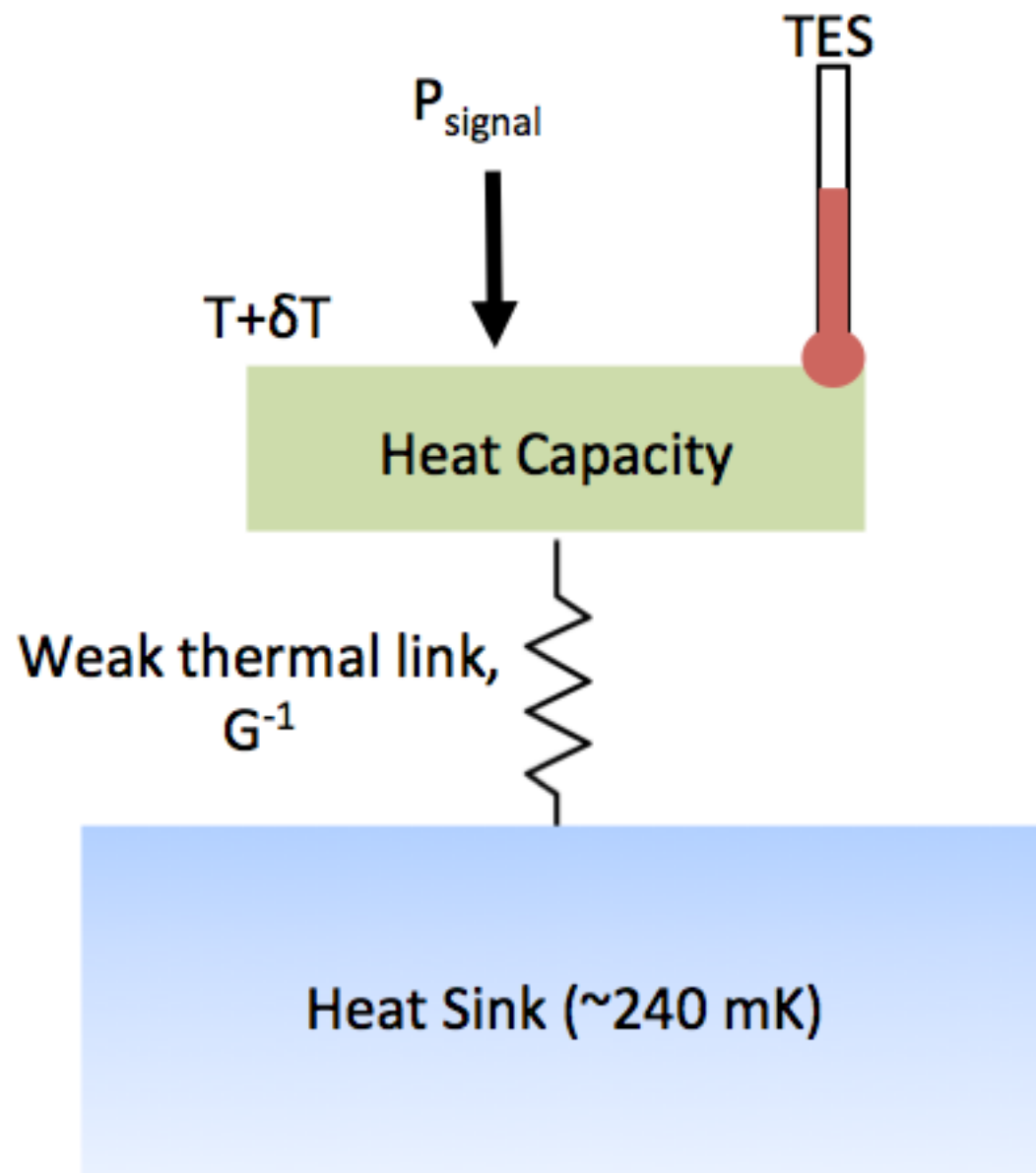
- Large angular coverage: degree angular scales for inflation, arcmin angular scales for lensing... minimum 3 arcmin resolution
- Large sky coverage: 20,000 sq deg ($f_{sky} \sim 0.5$)
- Lots of detectors: 500,000
- Broad frequency coverage for foreground removal: 40 - 240 GHz
- Target noise of 1 μ K-arcmin over 50% of the sky starting 2020, observing for 5 years

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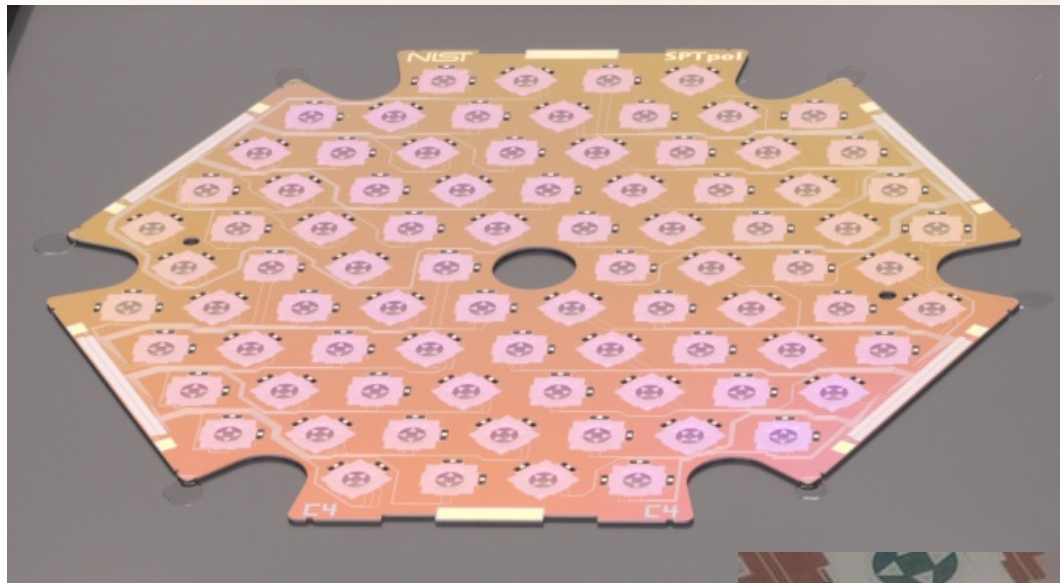
Primary technical development
is one of scale

Core technology: TES bolometers

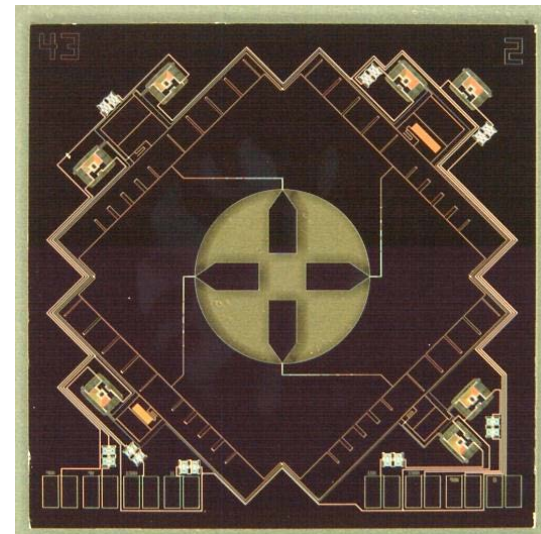
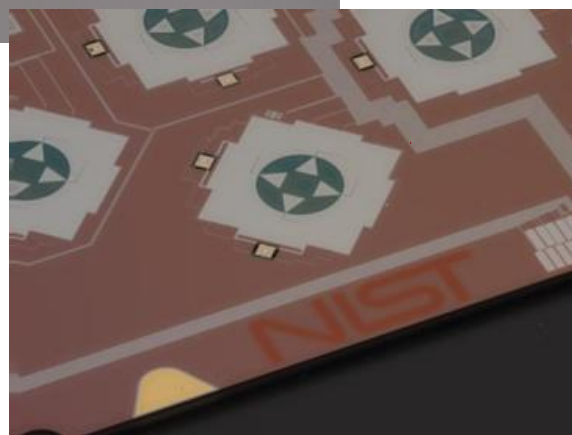


Invented by HEP for
Dark Matter detection

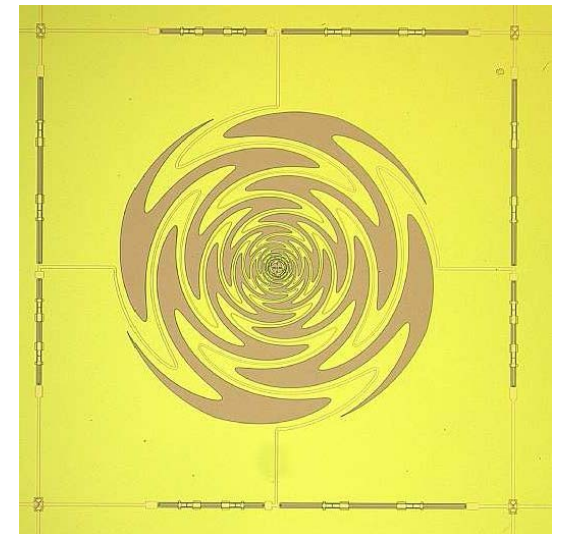
Core Technology: TES polarimeters



150-GHz feedhorn-coupled TES polarimeters deployed at the South Pole and in the Atacama



Multichroic feedhorn coupled polarimeter

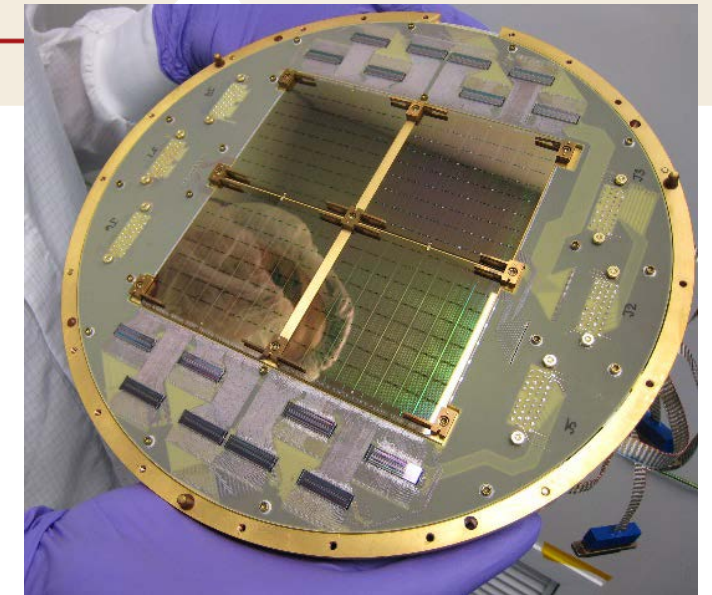


Multichroic lens-coupled polarimeter

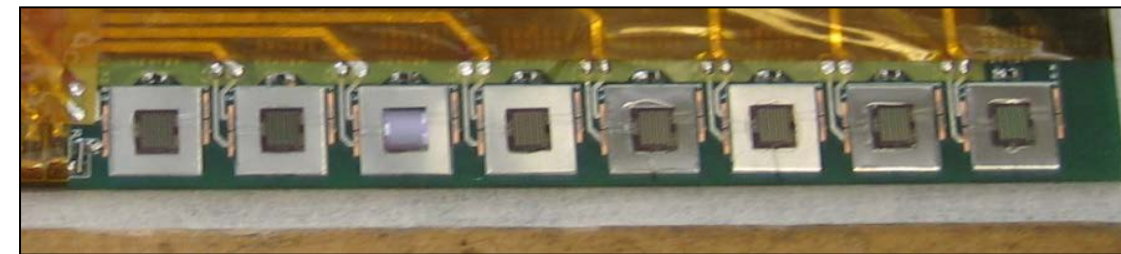
- The scale and performance of CMB polarimeters must continue to improve to meet the needs of a stage 4 experiment.
- New direction: larger arrays of multi-frequency (multi-chroic) CMB polarimeters
- New direction: increased integration of sensor and multiplexer components.

Core Technology: SQUIDs

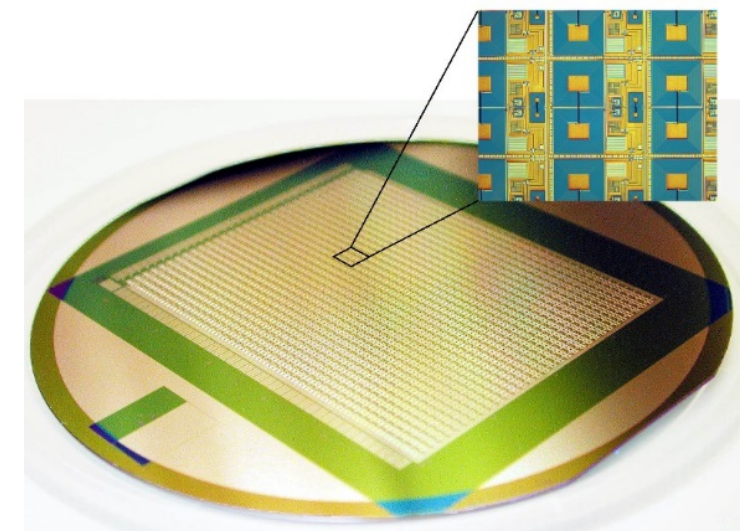
- TES arrays are doubling in size every year. We must stay on this 'Moore's Law' curve to enable a stage 4 experiment.
- This doubling requires advances in multiplexed readout electronics and Superconducting Quantum Interference Devices (SQUIDs). The maximum detectors per output channel in present CMB experiments is 32.
- Important new direction: multiplexing TESs using SQUIDs in superconducting microwave resonators enables thousands of detectors per output channel.



BICEP-2 with SQUID mux



SQUIDs for SPTpol and **SPT-3G**



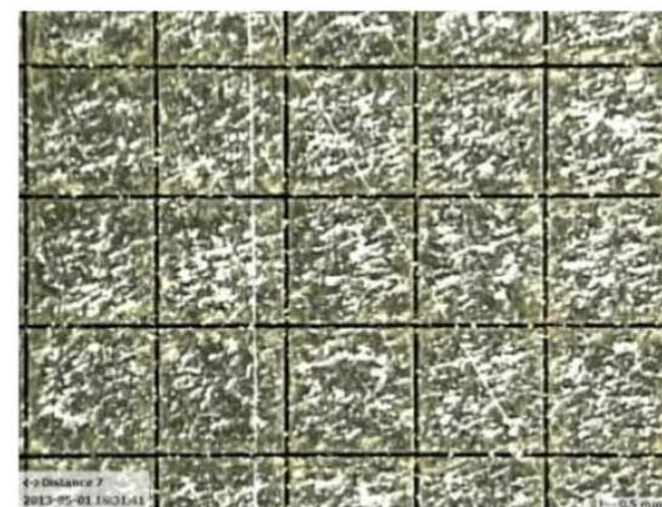
1,280-channel SQUID multiplexer₉

Core Technology: large mm-wave components

60cm alumina lens

delivered to
SLAC

for metrology



**Epoxy-based
AR coating
w/ grooves**

survived cryogenic
cycles

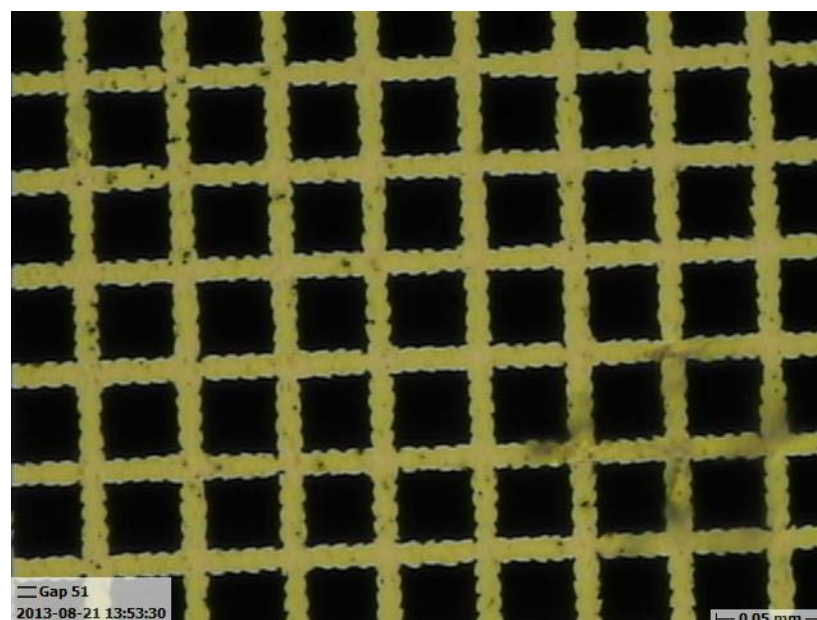
30 um cut on 1 mm grid - macro

**Laser machined
IR filters**

**24" diameter
(~SPT-3G window)**

15 μ m features
3 μ m mylar substrate

Mm/IR
properties verified



Technical Path for CMB-S4

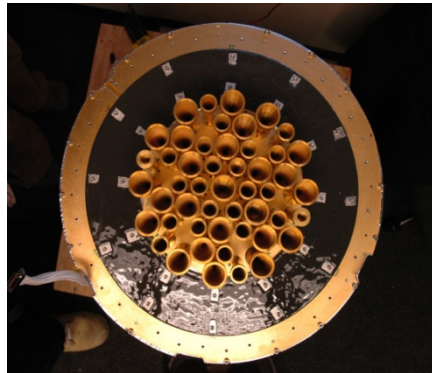
- **Multiplexed TES Readout:** modest improvements of existing successful multiplexer technologies. New microwave-based multiplexers may provide lower cost options with broader applicability
- **Large Cryogenic Optics:** large aperture, large optical bandwidth cryogenic optics. Incremental improvement over Stage-III
- **Improved Production Reliability:** develop fabrication processes which control and stabilize material properties to achieve consistent high yield
- **Increased Production Volume and Throughput:** requires facilities with dedicated tooling and mass production throughput. Extensive QA testing program.
- **Computing:** data rate ~ 1 TB per day. $\sim 10,000$ -times more observations per pixel compared to Planck

Evolution of CMB experiment

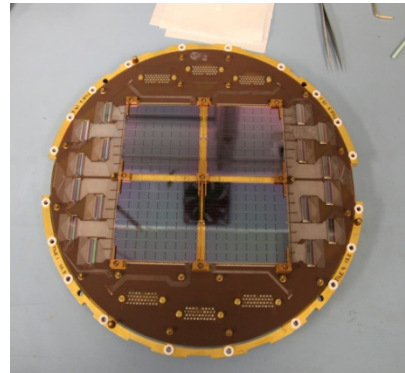
- HEP involvement in CMB has historically been small efforts focused on specific technical contributions (e.g.: multiplexing, detector fabrication and development, broadband antennas, MMICs)
- Moving from Stage-II to Stage-III and beyond, there is a consolidation of effort from multiple small experiments towards a few larger experiments
- There is increased involvement and impact from national lab resources

CMB Focal Planes and National Labs

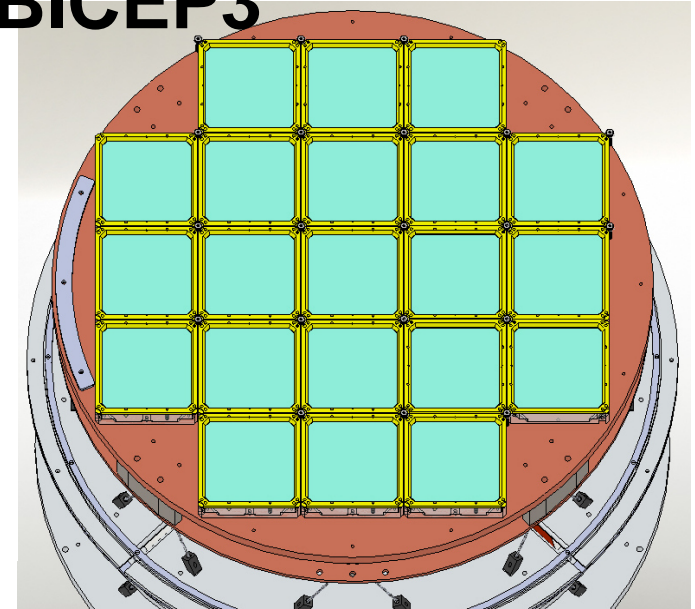
BICEP



BICEP2



BICEP3

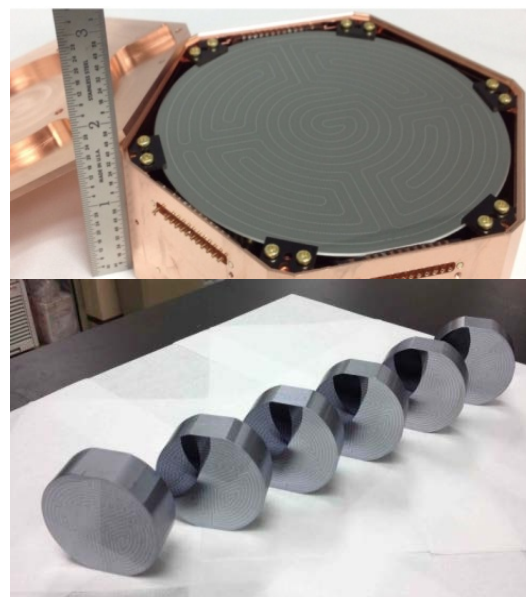


Fermi-LAT



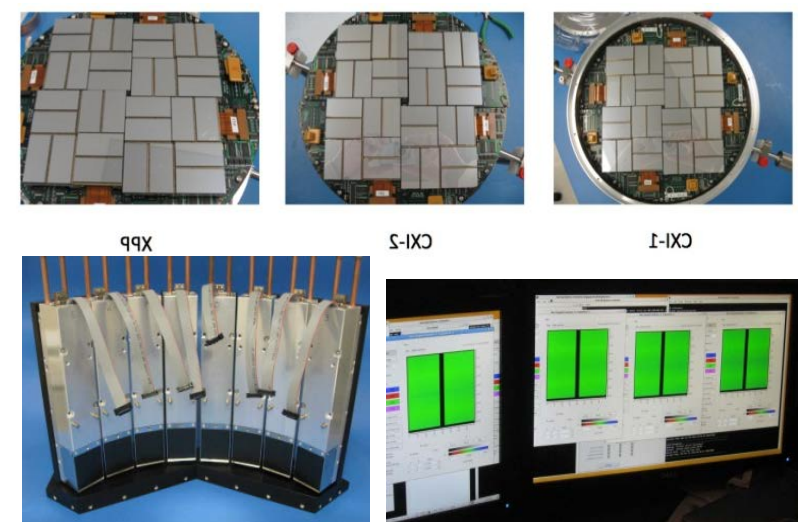
- 80 square meters of silicon sensors
- Silicon LAT assembled at SLAC

Super CDMS



- Scaling up of Germanium sensors and fab throughput

LCLS Detectors



- R&D with Cornell Univ.
- SLAC made 10 million pixels in total so far via robotic assembly

Summary

- CMB-S4 will fully exploit B-mode measurement. Primary challenge is one of scale.
- TES Core technology. HEP invented technology. Major impact on Stage-II incl. first lensing B-mode detection. Focus on mass production for CMB-S4.
- Change from historical *Modus Operandi*... consolidation of effort. Increased contribution/leadership from national labs.
- Impact: $\sigma(r) = 0.001$; $\sigma(N_{\text{eff}}) = 0.02$; $\sigma(\Sigma m_\nu) = 16 \text{ meV}$